PLASMONIC PHOTON SORTERS AND THEIR POTENTIAL FOR USE IN COMPACT MULTISPECTRAL IMAGERS AT VISIBLE AND INFRARED WAVELENGTHS

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ABSTRACT

Spectral imaging extracts rich information from the incoming light and has many military applications. Polarimetric imaging is also an active field of study with many potential applications. Many sensor technologies exist for spectral and polarimetric imaging, but these generally involve scanning or subsampling, since the dataset is three-dimensional while photodetector arrays are at most two-dimensional. Recently, it has been shown how surface plasmons may be used to "sort" photons arriving at a detector array by placing plasmonic antenna structures on top of the array. Each antenna structure concentrates light of a particular wavelength and/or polarization onto one detector element. Importantly, the antennas of a group of neighbouring detector elements are overlapped to form a "superpixel" capable of separating different components of the incoming light. Thus photons of different wavelengths arriving at the same location on the antenna structure may be routed to different detector elements. This has potential for use in snapshot multispectral and polarimetric imaging. The photon sorting capability has been demonstrated experimentally in the visible spectral range. No fundamental difficulties are expected in translating these results into the thermal infrared spectral range. Indeed, the antenna structures for thermal infrared wavelengths will be easier to fabricate due to the relatively long wavelength. The photon sorter concept has some specific issues and limitations, most importantly the polarization-dependent coupling efficiency which leads to reflection loss of a large fraction of the incoming light. However this may not be problematic in the 8 to 12 μm spectral range, where the number of photons per frame time is usually larger than the charge collection capacity of a photovoltaic detector. More work remains to map out the potential and the limitations of photon sorters, but their unique properties make them an interesting candidate for future multispectral and polarimetric thermal imaging systems.

1.0   INTRODUCTION

Spectral imaging is interesting in a variety of military applications, essentially because it collects information related to the chemical composition of imaged objects. Spectral images are three-dimensional data sets, with wavelength as the third dimension, while photodetector arrays used for imaging are generally limited to two dimensions. Therefore, spectral imaging techniques usually employ some kind of scanning or subsampling to form an image. For example, common digital colour cameras use an array of band-pass filters over the detector array so that each spatial pixel samples one spectral band. This leads to subsampling of the image data cube, with loss of light and loss of information. In the thermal infrared, multiband detectors have been made by stacking semiconductor layers with different bandgaps, as exemplified by Refs. 1 and 2, thereby avoiding subsampling. This comes at the expense of relatively complex growth, fabrication and readout of the detector elements, and is limited to 2-3 spectral bands.

Polarimetric imaging also has an interesting application potential, as the polarization state of incoming light provides information about the surface structure of imaged objects. Polarimetric imaging has many analogies to spectral imaging, including the fact that it suffers from the limitation of 2D detector arrays. A

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Spectral imaging extracts rich information from the incoming light and has many military applications. Polarimetric imaging is also an active field of study with many potential applications. Many sensor technologies exist for spectral and polarimetric imaging, but these generally involve scanning or subsampling, since the dataset is three-dimensional while photodetector arrays are at most two-dimensional. Recently, it has been shown how surface plasmons may be used to "sort" photons arriving at a detector array by placing plasmonic antenna structures on top of the array. Each antenna structure concentrates light of a particular wavelength and/or polarization onto one detector element. Importantly, the antennas of a group of neighbouring detector elements are overlapped to form a "superpixel" capable of separating different components of the incoming light. Thus photons of different wavelengths arriving at the same location on the antenna structure may be routed to different detector elements. This has potential for use in snapshot multispectral and polarimetric imaging. The photon sorting capability has been demonstrated experimentally in the visible spectral range. No fundamental difficulties are expected in translating these results into the thermal infrared spectral range. Indeed, the antenna structures for thermal infrared wavelengths will be easier to fabricate due to the relatively long wavelength. The photon sorter concept has some specific issues and limitations, most importantly the polarization-dependent coupling efficiency which leads to reflection loss of a large fraction of the incoming light. However this may not be problematic in the 8 to 12 ìm spectral range, where the number of photons per frame time is usually larger than the charge collection capacity of a photovoltaic detector. More work remains to map out the potential and the limitations of photon sorters, but their unique properties make them an interesting candidate for future multispectral and polarimetric thermal imaging systems.

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**PLASMONIC PHOTON SORTERS AND THEIR POTENTIAL FOR USE IN
COMPACT MULTISPECTRAL IMAGERS AT VISIBLE AND INFRARED WAVELENGTHS**

recent review of polarimetric imaging[3] points out that polarimetric imagers based on a single detector array have many advantages. Such systems, exemplified by Refs. 4 and 5, employ individual polarizers over each detector element. In analogy with filter arrays of colour cameras, this leads to spatial subsampling of the polarimetric signal, and some form of interpolation is necessary to estimate the polarization state of each image pixel.

Surface plasmons (SPs) have generated considerable interest in recent years due to their potential in optics and sensing among others[6-10]. We have recently shown that SPs enable "photon sorting" devices[11]. These could be integrated on a detector array to avoid the spatial subsampling inherent in conventional techniques used for spectral or polarimetric imaging. Here we review from Ref. 11 the concept of plasmonic photon sorters and the initial experimental results obtained in the visible and near-infrared spectral range. We then discuss the outlook for employing these techniques at thermal infrared wavelengths.

2.0 SURFACE PLASMONS AND THE CONCEPT OF PHOTON SORTING

SPs are essentially light waves trapped at a metal surface by their interaction with the free electrons in the metal. Their properties can be controlled by texturing the metal surface. In the context of spectral and polarimetric imaging, apertures surrounded by periodic grooves[12-14] are of particular interest. The periodic grooves act like an antenna for the incoming light by converting it to SPs and enhancing the transmission through the aperture. The transmission through such structures can be selective to wavelength and polarization.

Figure 1 gives an example of one such aperture structure where a single subwavelength hole is surrounded by concentric grooves, known as a Bull's eye structure. The transmission peak wavelength λ_{SPP} of the aperture can be tuned by controlling the groove periodicity P (Fig. 1b) as predicted by equation (1) for normal incidence illumination:

$$\lambda_{SPP} = P \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \quad (1)$$

Here ε_m and ε_d are the dielectric constants of the metal and the dielectric in immediate contact with the metal surface. The peak is normally red-shifted compared to equation (1) due to Fano-type interaction[15][16]. The transmission spectrum is also modulated by the other structural parameters such as groove depth, width, aperture shape and size[8,14].

The SPs give rise to intense electromagnetic fields at the central hole. The flux per unit area through the aperture can be larger than that of the incident light, confirming that the grooves act as an antenna, collecting light laterally from an area around the hole[8]. This extraordinary transmission phenomenon is very important here, as it allows for useful light collection efficiencies even though the apertures represent only a small fraction of the surface of the device.

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**PLASMONIC PHOTON SORTERS AND THEIR POTENTIAL FOR USE IN
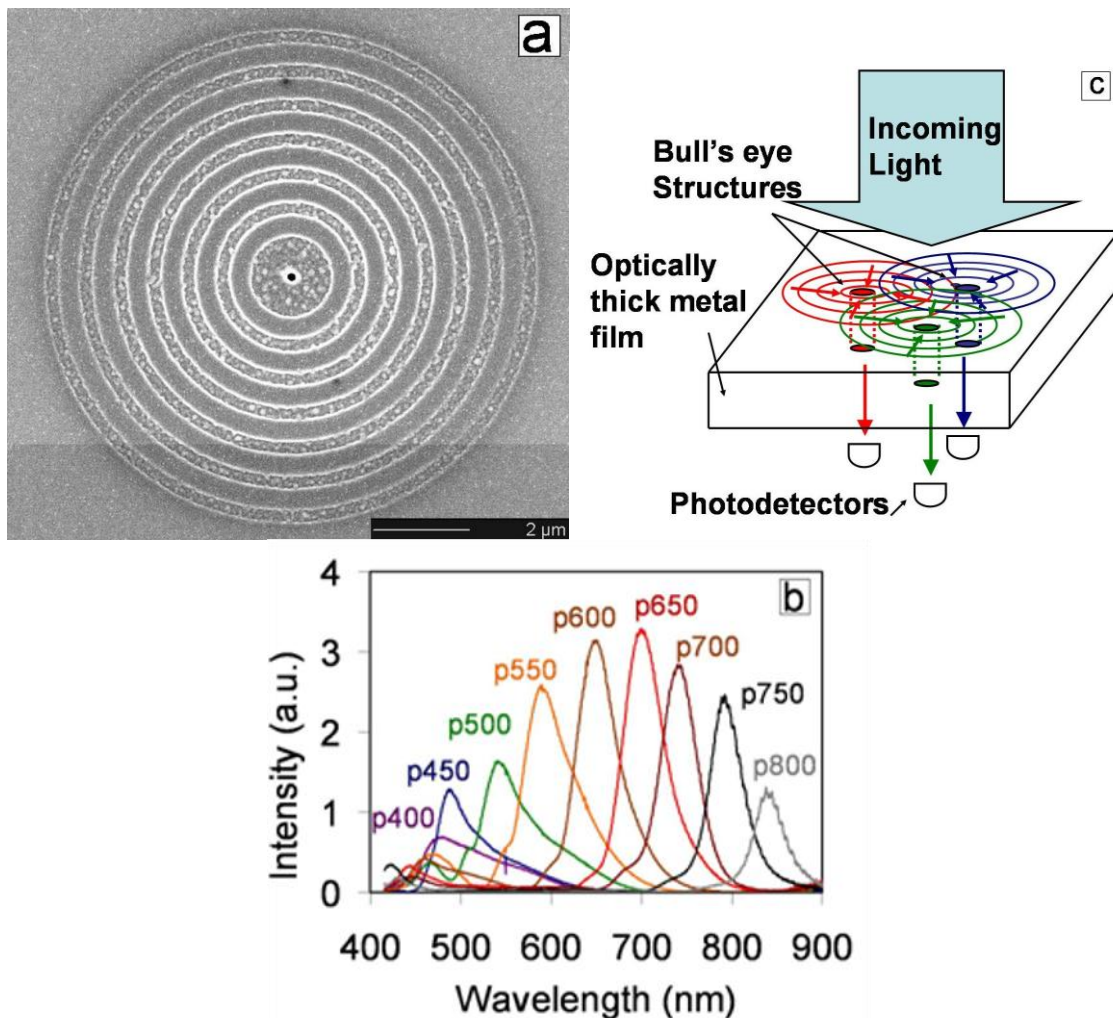COMPACT MULTISPECTRAL IMAGERS AT VISIBLE AND INFRARED WAVELENGTHS**

**Figure 1 Basic bull's eye structure for photon sorting. a: Bull's eye structure milled by FIB in a
300 nm thick Ag film on glass substrate. Dimensions: Central hole diameter d=170 nm, with 6
circular grooves (width 150 nm, period 800, depths varying linearly from 150 nm (central ring) to
10 nm (outer ring)). b:, Transmission spectrum for bull's eye structures with the same
dimensions as in 1a for groove periods varying from 400 to 800nm. c: Sketch of spatial filtering
process of the incoming white light through 3 overlapping bull's eye structures into three
distinct photodetectors.**

In Ref. [11], we proposed a class of devices consisting of overlapping light collection structures as illustrated in Fig. 1c). The key concept here is that each such structure would collect light over a certain frequency range and be able to redirect it to its central aperture even from the region where it overlaps with other collectors. With photodetectors placed underneath the apertures, we would then obtain a miniature device capable of recording information about the spectrum of light incident on the overlap area. Such a device can be used as the pixel unit in an image sensor consisting of an array of such "superpixel" units. The array may be placed in the focal plane of an imaging lens, resulting in a compact spectral imaging system. The simultaneous collection of different wavelengths from the same area contrasts with, for example, the standard Bayer filter approach to spectral imaging where each color is recorded on a separate pixel with the resulting loss of resolution, band registration and throughput.
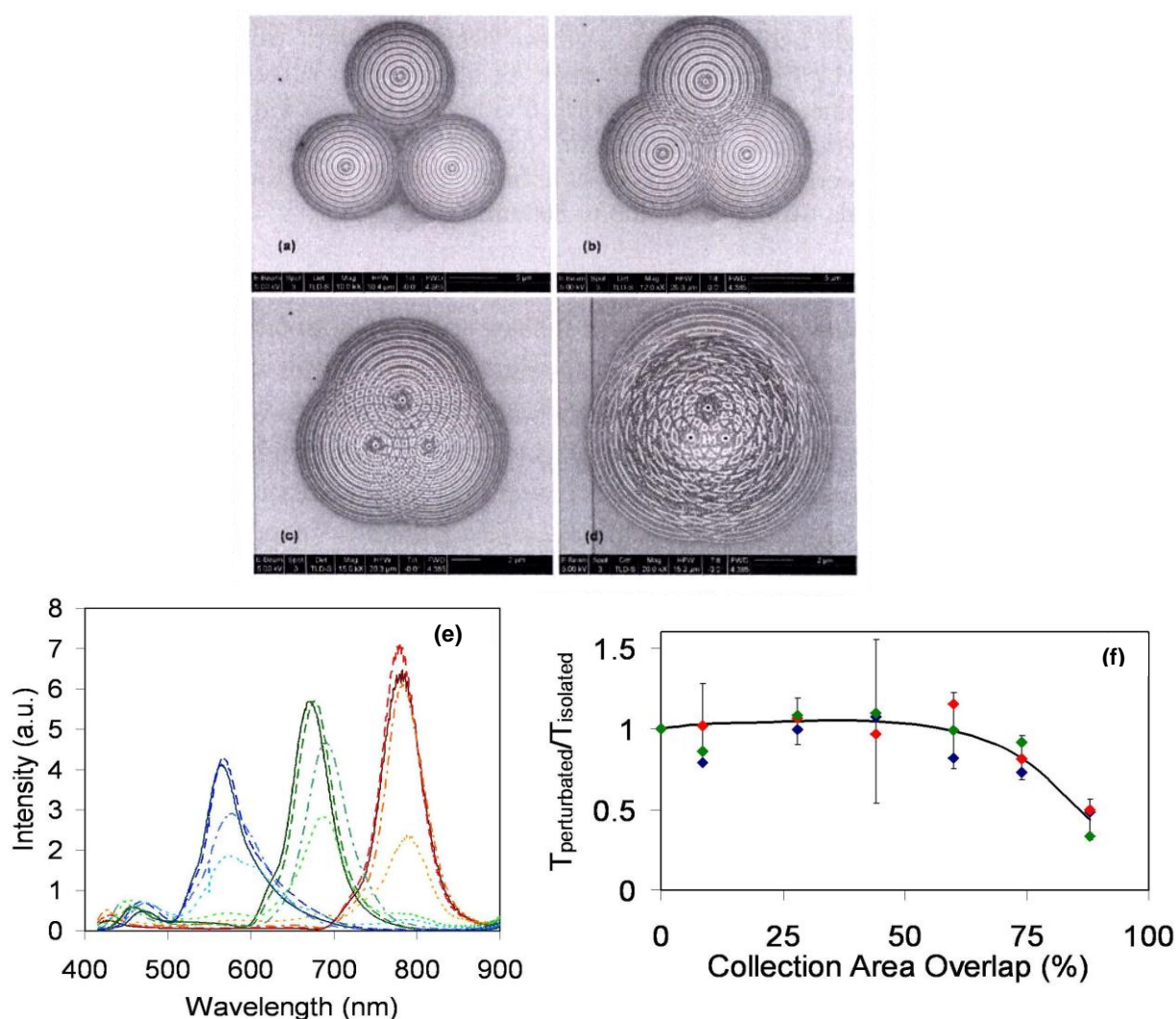
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**PLASMONIC PHOTON SORTERS AND THEIR POTENTIAL FOR USE IN
COMPACT MULTISPECTRAL IMAGERS AT VISIBLE AND INFRARED WAVELENGTHS**

Figure 2 Photon sorting efficiency of triple bull's eye structure. a to d:, Triple bull's eye structures with periods 530 nm, 630 nm and 730 nm, fabricated with different degree of overlap. e: Transmission spectra measured at each hole as a function of structural overlap (bold lines separated bull's eye structures, dashed line 44% overlap, dashed-dotted 77%, dotted lines 88%). The depth parameters are the same as in Figure 1a. f: Transmission peak intensities normalized to the isolated bull's eye peaks shown in b as a function of overlap. The error bars reflect the spread in measured values for 6 data points and the points the average for each colour peak.

3.0   EXPERIMENTAL RESULTS

Triple bull's eye structures were milled by focused ion beam (FIB) lithography in an optically thick Ag film as shown in Fig. 2a)-f) with periods adjusted to give rise to resonances at 3 different wavelengths. As can be seen in Fig. 2e), the shape of the transmission peak associated with one bull's eye is hardly changed by the presence of the others as the hole to hole distance is decreased. In addition, each bull's eye transmits very little light corresponding to the resonances of the adjoining structures. To characterize the overlap effect more precisely, the peak transmission intensity relative to the isolated bull's eye structures versus the percentage spatial overlap between the 3 bull's eye structures is plotted in Fig. 2f). Surprisingly, the peak intensity at each resonance drops far more slowly than the overlap. At 60% overlap, the collected efficiency is not altered within experimental error.
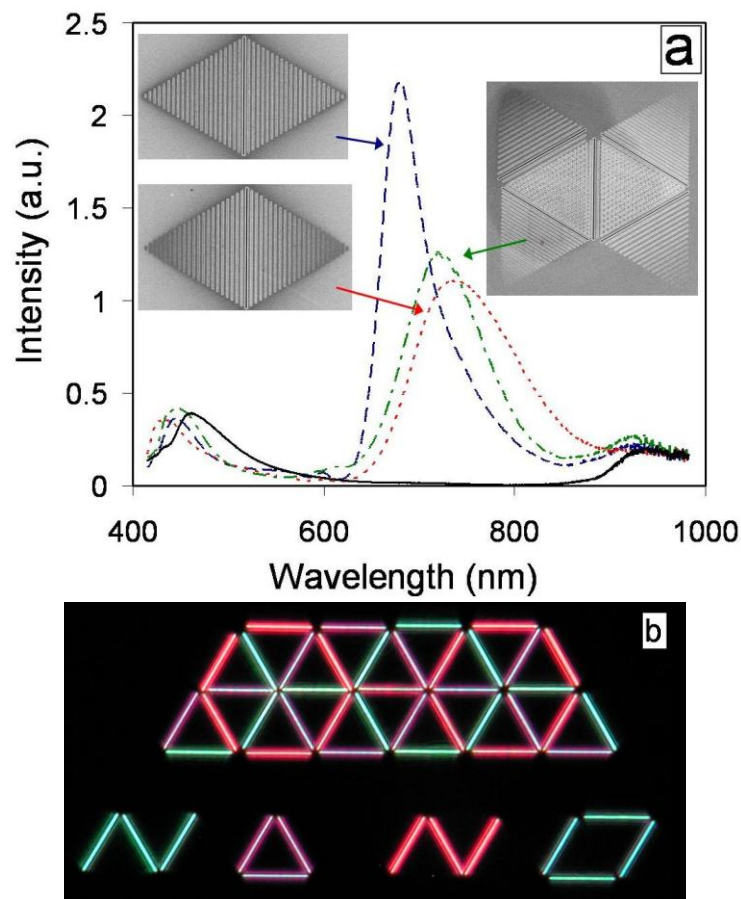
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**PLASMONIC PHOTON SORTERS AND THEIR POTENTIAL FOR USE IN
COMPACT MULTISPECTRAL IMAGERS AT VISIBLE AND INFRARED WAVELENGTHS**

Figure 3 Photon sorting with slit structures. a, Transmission spectra of a single slit (length 15μm, width 170nm) surrounded by periodic grooves(period 600nm) with constant groove depth (100nm) (blue dashed), a groove depth gradient from 150nm (inner groove) to 5nm (outer groove) (red dotted) and with the groove depth gradient integrated in a lattice (green dashed-dotted) with the light polarized perpendicular and parallel (black line) to the slits. SEM images of these structures are shown as insets. b, Microscope picture of the output from a lattice of such slits of periods 450nm (blue purple slits), 500nm (green slits), 580 nm (red slits).

Structures shown here differ from a traditional bull's eye structure by the introduction of a linear groove depth gradient, with the deepest grooves closest to the aperture. This, we found, diminishes the perturbation of the collection efficiency of each bull's eye due to the presence of the others by decreasing the added roughness introduced by the overlapping grooves near each aperture. The only significant trade-off is a slight broadening and decrease of the transmission peaks as shown for the next structures.

Other light collection structures can be made sensitive to both polarization and wavelength. A basic unit structure is a slit surrounded by parallel periodic grooves designed to fit a triangular lattice whose transmission spectrum can be tuned by controlling the geometrical parameters[8,14]. An example of such a structure is shown as inset in Fig. 3a), with and without a groove depth gradient, together with the corresponding transmission spectra, illustrating the effect of modulating the groove depth as discussed above. The addition of grooves associated with neighbouring slits does not affect significantly the transmission of the central slit as shown in Fig. 3a). However, the transmission spectrum depends on the polarization of the incoming light, coupling most efficiently when polarized perpendicular to the slit. With polarization parallel to the slit, the transmission resonance vanishes (Fig. 3a).

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**PLASMONIC PHOTON SORTERS AND THEIR POTENTIAL FOR USE IN
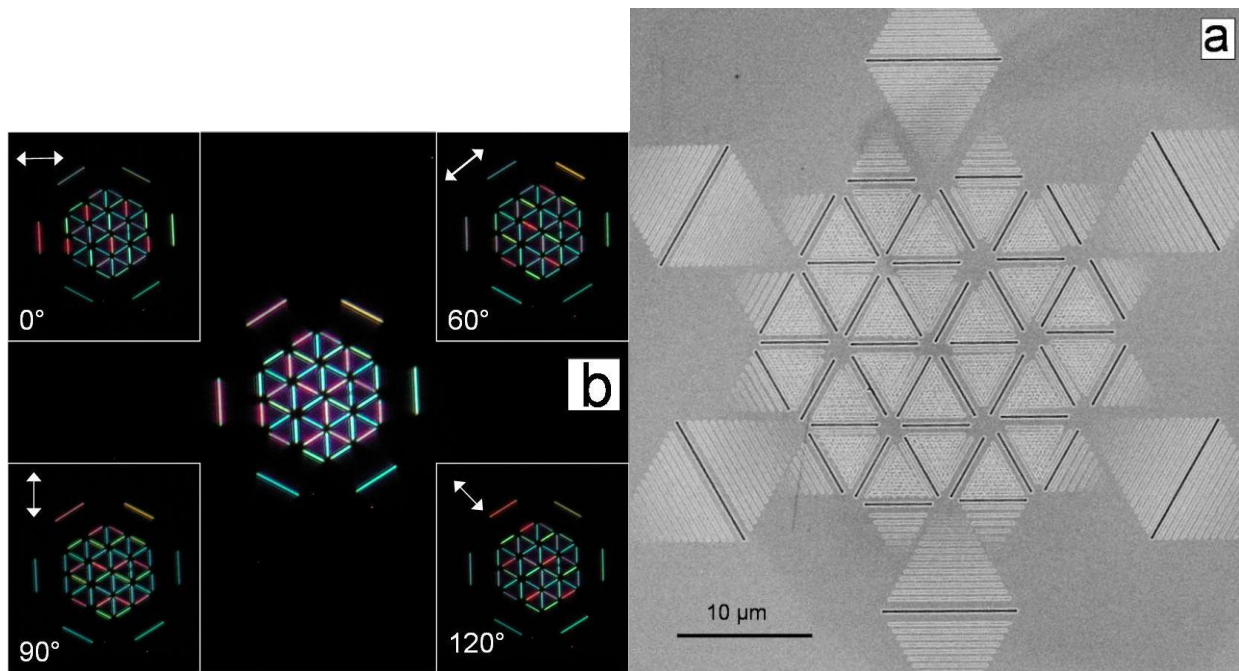COMPACT MULTISPECTRAL IMAGERS AT VISIBLE AND INFRARED WAVELENGTHS**

Figure 4 Polarization response of slit-groove lattice. a, SEM image of a 2 D lattice with downsized slits (length 5μm, width 170 nm) with grooves (width 150nm, linear depth gradient from 150nm to 10 nm) for 3 periods (450, 500 and 580nm) surrounded by slits of length 10 μm with periods varying from 450 nm (blue) to 580 nm (red). b, Microscope picture of this structure when illuminated with unpolarized light (center) and polarized light (boxes). The overall illuminating intensity is weaker for the polarized images due to the attenuation of the polarizer.

To be useful for spectral and polarization imaging, such basic unit structures should be integrated into a lattice and still preserve the spectral selectivity. This is clearly achieved in Fig. 3b) where different colours are brightly visible despite the very narrow slits (170 nm) and the overlap of three different groove structures in each triangle delimited by the slits. Here, the light is reimaged on a detector array through a microscope. It is clear, however, that in a real system the plasmonic structure and photodetector array could be integrated into a monolithic image sensing device.

We can estimate the transmission efficiency normalized to the area of the slit in this lattice and we find that it is on the order of 5 to 10, as expected from the addition of an antenna structure around the slit. For most imaging applications, it is not the enhancement factor per slit that is important, but the absolute transmission of the whole device. In the above lattice, the slit length was 15 μm and the number of grooves was around 20. It is known that the transmission intensity increases with the number of grooves, but rapidly saturates around 10 grooves due to the limited propagation length of SPs on a corrugated surface[17]. Downsizing the triangular lattice so that it is comprised of fewer grooves should therefore preserve the signal strength per slit but increase the absolute transmission since the density of slits increases. We tested this by reducing the slits to a 5 μm length and the number of grooves to 7 (Fig. 4). The intensity per slit remained essentially unchanged compared to the structure in Fig. 3b), but the absolute transmission increased as expected. Absolute transmission from 1,5 to 15% were observed depending on the different parameters like the aperture width and assuming conservatively that all the light is collected by our microscope objective. The important point here is that absolute transmission of the whole device of 10% or higher is observed even though the structures have not been fully optimized. In comparison, even the standard Bayer filter approach[18], where 4 separate pixels collect 3 different colors, must have efficiencies less than about 25% for at least two colors.

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PLASMONIC PHOTON SORTERS AND THEIR POTENTIAL FOR USE IN COMPACT MULTISPECTRAL IMAGERS AT VISIBLE AND INFRARED WAVELENGTHS

Figure 4b) also shows the response of the lattice to 4 different polarizations of the incident light. As the polarization is rotated, different slits light up, with a maximum when they are perpendicular to the electric field. When the polarization is parallel to the slit, only the short wavelengths below the cutoff wavelength of the slit are transmitted, giving a blue hue in the image. The color with a given polarization not collected at one slit will be collected in neighbouring slits oriented at 60°. Interpolation will therefore be necessary to extract the polarimetric information recorded by this particular device.

4.0   ASPECTS OF PHOTON SORTING IN THE THERMAL INFRARED

In a photodetector array, light incident on each detector element generates photoelectrons which are collected on a capacitor within the pixel unit (either on a separate capacitor or on the light-sensitive element itself). At the end of an integration time, the signal is read out by some means, and the capacitor is reset. In the thermal infrared, and particularly in the long wave infrared (LWIR) band from 8 to 12 μm wavelength, the photon flux from ambient-temperature scenes tends to be large compared to the ability of pixel elements to store photogenerated charge. Therefore, the losses in the photon sorter may be acceptable in many LWIR applications.

As an example, consider video-rate imaging of an ambient-temperature scene using the full LWIR band. State-of-the-art detector arrays may have a pixel pitch of about 15 μm and a charge collection capacity on the order of 10^7 electrons. During one video frame time of 20 ms, the number of photons arriving will be on the order of 10^9 electrons, somewhat dependent on the characteristics of the camera. Thus the number of photons exceed the charge collection efficiency of typical commercial detectors by a factor on the order of 100. (Of course, this factor tends to be independent of the pixel area since capacitance and optical power both scale proportional to pixel area.) Thus the integration time will have to be set significantly shorter than the frame time. Usually the spectral range is somewhat narrower, but the example nonetheless shows that in the LWIR there is significant margin on the amount of light in many cases.

Generally, spectral and polarimetric imaging tends to be more challenging in the thermal infrared due to the thermal radiation emitted from uncooled parts of the optics, which must be prevented from reaching the detector elements. Such radiation can otherwise become significant in comparison to the signal radiation after it has been split into several weak spectral components or polarization components. The photon sorter is one of the relatively few sensing concepts where decomposition of light occurs at the focal plane. This minimizes the potential for unwanted radiation since the decomposed light travels only a very short distance within the cooled detector enclosure.

In the thermal infrared, many metals can be used including Au which has many favourable properties, and plasmon resonances tend to be sharper. It is also worth noting that the plasmonic structures scale with wavelength, to a good approximation. Therefore photon sorters for the LWIR can be fabricated using easily accessible lithography techniques. A wide range of microfabrication techniques can also be employed to make photon sorters in the thermal infrared.

5.0   DISCUSSION

Among the many spectral and polarimetric imaging techniques[3,19,20], the concept proposed here is one of the few which allow simultaneous acquisition of a complete image. This is also the case for commercial colour cameras based on Bayer filter arrays[18], stacked photodetector structures[1,2,21] or "3-CCD" techniques using beam splitters and separate detector arrays, as well as many-band techniques based on tomographic reconstruction[22] or image replication[23]. However, these techniques have disadvantages due to incomplete sampling of the image, limited photon efficiency or complex fabrication. The in-plane photon sorting capacity of surface plasmons offers new opportunities for improvement in spatial resolution, band registration, band count, throughput, simultaneity or simplicity, depending on what

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**PLASMONIC PHOTON SORTERS AND THEIR POTENTIAL FOR USE IN
COMPACT MULTISPECTRAL IMAGERS AT VISIBLE AND INFRARED WAVELENGTHS**

technology it is compared with. Beyond 4-6 bands, most spectral imagers employ some form of scanning, which leads to spectral artifacts for nonstationary scenes and/or loss of throughput. This can potentially be overcome to some extent with photon sorters if they can be made with a larger number of bands than shown here.

The above results demonstrate experimentally the validity of the photon sorter concept. However further studies are needed to explore the opportunities and limitations of the concept, including the permissible number of spectral bands and the throughput of light. An important topic for further study is delineation of neighbouring superpixels, by truncating the device or introducing additional surface structuring, to reduce propagation between superpixels and obtain better defined pixel shapes in the spectral image. Another unexplored opportunity is the use of surface structuring on the exit side of the apertures. By appropriate structuring, the emerging light can be focused and beamed in the desired detection[17,24,25]. Thus it may be possible to have an arrangement of apertures that is different from the arrangement of underlying detectors.

It is interesting to note that the antenna effect of the plasmonic structure permits reduction in the underlying photodetector size, with potential gains in speed[26] and/or chip dimensions. For the LWIR band in particular, it is interesting to note that the diffraction limit of imaging optics implies a superpixel size which is very large compared to the minimum dimensions of current chip fabrication techniques. With the photon sorter, these fabrication capabilities can potentially be exploited to decompose the light according to wavelength or polarization within a diffraction-limited superpixel size.

In summary, the photon sorter concept has been experimentally verified, and there are several arguments in favour of using this technique for spectral or polarimetric imaging in the LWIR spectral band. Further work is needed to develop the concept into devices adapted for specific applications, and to find the limits on their performance. Like all spectral and polarimetric imaging techniques, the concept presented here is subject to limitations, notably coupling and propagation losses and some yet unknown limit on band count. On the other hand the concept has unique advantages due to the capacity of surface plasmons to be sorted in the detector plane, which opens new design opportunities worthy of further exploration.

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**PLASMONIC PHOTON SORTERS AND THEIR POTENTIAL FOR USE IN
COMPACT MULTISPECTRAL IMAGERS AT VISIBLE AND INFRARED WAVELENGTHS**

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